



Gasification of biomass in a fixed bed downdraft gasifier – A realistic model including tar

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ABSTRACT

This study presents a model for fixed bed downdraft biomass gasifiers considering tar also as one of the gasification products. A representative tar composition along with its mole fractions, as available in the literature was used as an input parameter within the model. The study used an equilibrium approach for the applicable gasification reactions and also considered possible deviations from equilibrium to further upgrade the equilibrium model to validate a range of reported experimental results. Heat balance was applied to predict the gasification temperature and the predicted values were compared with reported results in literature. A comparative study was made with some reference models available in the literature and also with experimental results reported in the literature. Finally a predicted variation of performance of the gasifier by this validated model for different air–fuel ratio and moisture content was also discussed.

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1. Introduction

Since 1973 the energy sources have been doubled in developed countries but the demand is still higher (Goyal et al., 2008). Mostly the demand of energy is fulfilled from the conventional fossil fuels such as coal, petroleum and natural gases. However, these energy sources will be depleted soon (Zainal et al., 2001). Use of renewable sources of energy is now increasing. One of the promising renewable sources of energy is biomass. Plant produces biomass continuously by the process of photosynthesis (Perez et al., 2002; Demirbas, 2001; McKendry, 2002). Gasification of biomass is a thermal process to convert it into a combustible synthetic gas. The main components of this gas are CH₄, H₂, CO, CO₂, H₂O and N₂ (Hindsgaul et al., 2000). However a variety of tars are also produced during the gasification reaction.

Jarunthammachote and Dutta (2007) developed an equilibrium model for predicting the composition of syngas in a downdraft waste gasifier for solid waste. It was further modified by multiplying the equilibrium constants with coefficients. Babu and Sheth (2004) developed another equilibrium model in which the effect of oxygen enrichment of air, preheating of air, steam to air ratio on gas composition, reaction temperature and calorific values were investigated. Ramanan et al. (2008) gasified de-oiled cashew shells in an autothermal downdraft gasifier. They developed an equilibrium model to predict this syngas composition under

varying operating parameters, viz., equivalence ratio (ER), reaction temperature (RT) and moisture content (MC). Melgar et al. (2007) combined the chemical equilibrium and the thermodynamic equilibrium of the global reaction to predict the final composition of the producer gas as well as its reaction temperature in a downdraft biomass gasifier. Roy et al. (2010) described a model of downdraft gasifier, considering thermodynamic equilibrium of species in the pyro-oxidation zone and kinetically controlled reduction reactions in the reduction zone. Sharma (2008) used the global reduction reactions using thermodynamic principles based on the stoichiometric approach. Tinaut et al. (2008) presented a one-dimensional stationary model of biomass gasification in a fixed bed downdraft gasifier. The energy exchange between solid and gaseous phases and the heat transfer by radiation from the solid particles were included with the mass and energy balance equations. Ptasiński et al. (2007) compared different types of biofuels for their gasification efficiency and benchmarked this against gasification of coal. Zainal et al. (2002) carried out an experimental investigation of a downdraft biomass gasifier using furniture wood and wood chips and the effects of equivalence ratio on the gas composition, calorific value and the gas production rate was reported. Jayah et al. (2003) presented results of an experimental testing to investigate their gasifier design under various conditions. Data produced during their experiment was used to validate a computer program, which was used to investigate the impact of those parameters on conversion efficiency. Dogru et al. (2002a) reported gasification of sewage sludge using a 5 kWe-throated downdraft gasifier. A pilot scale downdraft gasifier was used by Dogru et al. (2002b) to investigate

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gasification potential of hazelnut shells also. A full mass balance was reported including the tar production rate as well as the composition of the produced gas as a function of feed rate. Sheth and Babu (2009) used a downdraft biomass gasifier to carry out the gasification experiments with the waste generated while making furniture. The effects of air flow rate and moisture content on biomass consumption rate and quality of the produced gas generated were studied. Sharma (2009) obtained temperature profile, gas composition and its calorific value in both firing as well as non-firing mode in a 75 kWth, downdraft gasifier. Ratnadhariya and Channiwala (2010) experimentally studied molar distribution of gases along the length of a downdraft gasifier with different woody biomass. Skoulou et al. (2008) reported laboratory-scale gasification of olive kernels in fixed bed. Bottino et al. (2006) presented a model of a non-adiabatic methane steam reformer membrane reactor (MSRMR) working in equilibrium conditions. Yamazaki et al. (2005) investigated the changes in the amount and composition of tar with superficial velocity in a downdraft biomass gasifier. An ASPEN Plus simulation model complemented with FORTRAN subroutines for pressurized fluidized-bed gasification of biomass was reported by Hannula and Kurkela (2010). Experimental validation showed good agreement for some biomass. Experiment in a dual CFB gasifier of biomass was reported by Ngo et al. (2011). A three stage quasi-equilibrium model was also developed and validated with these results. Effects of crude glycerol loading on gas composition in co-gasification of hardwood chips in a downdraft gasifier was experimentally investigated by Wei et al. (2011).

In this study a realistic gasification model is developed with a representative composition of tar along with other components in the produced syngas. An equilibrium model is developed initially. Then coefficients are multiplied with equilibrium constants for closer approximation of actual gasification in non-equilibrium conditions also. Both elemental mass balance and energy balance are satisfied in the model, leading to the prediction of exit gas temperature and gas composition. Finally a performance analysis of the gasifier with this model was also discussed.

2. Methods

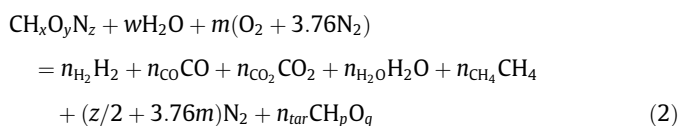
2.1. Formulation of the model

The dry biomass fuel can be expressed by a generalized unified molecular formula $\text{CH}_x\text{O}_y\text{N}_z$ where the subscripts x , y and z are determined from the ultimate analysis of the biomass.

$$x = \frac{\text{HMC}}{\text{CM}_\text{H}} \quad y = \frac{\text{OMC}}{\text{CM}_\text{O}} \quad z = \frac{\text{NMC}}{\text{CM}_\text{N}} \quad (1)$$

where M_C , M_H , M_O and M_N are the molecular weights of carbon, hydrogen, oxygen and nitrogen respectively and C, H, O and N are mass fractions of those elements.

The generalized biomass gasification reaction can be represented as (Goyal et al., 2008).



where n_{H_2} , n_{CO} , n_{CO_2} , $n_{\text{H}_2\text{O}}$, n_{CH_4} , n_{N_2} and n_{tar} are the number of moles of H_2 , CO , CO_2 , H_2O , CH_4 and N_2 and tar respectively, m is the air moles and w is the moisture associated with the biomass. CH_pO_q represents the tar. The elemental balance for the global gasification reaction (Eq. (1)), leads to the following equations.

Carbon balance:

$$n_{\text{CO}} + n_{\text{CO}_2} + n_{\text{CH}_4} + n_{\text{tar}} - 1 = 0 \quad (3)$$

Hydrogen balance:

$$n_{\text{H}_2} + 2n_{\text{H}_2\text{O}} + 4n_{\text{CH}_4} + pn_{\text{tar}} - x - 2w = 0 \quad (4)$$

Oxygen balance:

$$n_{\text{CO}} + 2n_{\text{CO}_2} + n_{\text{H}_2\text{O}} + qn_{\text{tar}} - W - 2m - y = 0 \quad (5)$$

As different tars are produced in a gasification reaction through complex set of reactions, predicting tar species in the product gas using any numerical technique is very difficult. Due to that reason representative tar composition as reported in the literature was used as an input parameter in the model. The present study therefore considered the tar composition as well as its mole fraction in the product gases as an input parameter in the model. Yamazaki et al. (2005) classified the tar as gravimetric tar and GC-detectable tar. According to their reported result the maximum tar yield was 4.5% (mass percentage). The present study therefore considered the same value of the tar yield and considered the corresponding mole value (n_{tar}) as an input parameter in the gasification model. The representative formula of tar was taken from Tinaut et al. (2008) and its formula was $\text{CH}_{1.003}\text{O}_{0.33}$.

Three more equations were obtained by considering the equilibrium of the water gas shift reaction, methane reaction and methane reforming reaction as follows:

Water–gas shift reaction: $\text{CO}_2 + \text{H}_2\text{O} = \text{CO} + \text{H}_2$.

$$K_1 = \frac{n_{\text{CO}_2} \times n_{\text{H}_2}}{n_{\text{CO}} \times n_{\text{H}_2\text{O}}} \quad (6)$$

where the equilibrium constants K_1 is evaluated from the following relation (Pedroso et al., 2005), T being the temperature in K.

$$K_1 = e^{\left\{\left(\frac{4276}{T}\right) - 3.961\right\}}$$

Methane reaction: $\text{C} + 2\text{H}_2 = \text{CH}_4$.

$$K_2 = \frac{n_{\text{CH}_4} \times n_{\text{total}}}{n_{\text{H}_2} \times n_{\text{H}_2}} \quad (7)$$

The equilibrium constant K_2 is evaluated from the relation proposed by Zainal et al (2001).

$$\begin{aligned} \ln(K_2) = \frac{7082.842}{T} - (6.567) \times \ln T + \frac{(7.467 \times 10^{-3}) \times T}{2} \\ - \frac{2.167 \times 10^{-6}}{6} \times T^2 + \frac{0.702}{2 \times T^2} + 32.541 \end{aligned}$$

Jarunghammachote and Dutta (2007) develop their model by considering Eqs. (3)–(7). During their validation with the experimental results of Jayah et al. (2003), it was observed that to validate their model with the experimental results more amount of air was to be considered as shown in Tables 1 and 2. The significance of this observation was that to satisfy the mole percentage of N_2 higher amount of air was required in the model proposed by Jarunghammachote and Dutta (2007). So to overcome that difficulty the methane reforming reaction was incorporated within the model excluding the carbon balance initially.

Methane Reforming Reaction: $\text{CH}_4 + \text{H}_2\text{O} = \text{CO} + 3\text{H}_2$

$$K_3 = \frac{x_{\text{CO}} \times x_{\text{H}_2}^3}{x_{\text{CH}_4} \times x_{\text{H}_2\text{O}}} \quad (8)$$

where x represents the corresponding mole fraction of the individual species.

The equilibrium constant K_3 is expressed as (Bottino et al., 2006).

$$K_3 = 1.198 \times 10^{13} e^{-\frac{26830}{T}}$$

After solving the Eqs. (4)–(8) simultaneously with the help of Athena Visual Studio® the values of n_{CO} , n_{CO_2} , n_{CH_4} and n_{tar} were calculated to satisfy the carbon balance with a reasonable accuracy.

Table 1

Comparison of present model with the model of Jarunghammachote and Dutta (2007) and experiments by Jayah et al. (2003).

Biomass composition	w (kmol of moisture per kmol of biomass)	m (kmol of air per kmol of biomass)	Gas composition (mole % dry basis)		
			Present model	Model of Jarunghammachote and Dutta (2007)	Experimental results of Jayah et al. (2003)
CH _{1.54} O _{0.622} N _{0.017}	16%	0.33	H ₂ -18.07	H ₂ -18.04	H ₂ -17.00
			CO-18.00	CO-17.86	CO-18.40
			CH ₄ -0.28	CH ₄ -0.11	CH ₄ -1.3
			CO ₂ -11.73	CO ₂ -11.84	CO ₂ -10.6
			N ₂ -51.92	N ₂ -52.15 For m = 0.4647	N ₂ -52.7
CH _{1.54} O _{0.622} N _{0.017}	14%	0.39	H ₂ -14.00	H ₂ -18.03	H ₂ -12.5
			CO-19.95	CO-18.51	CO-18.9
			CH ₄ -0.31	CH ₄ -0.11	CH ₄ -1.2
			CO ₂ -10.36	CO ₂ -11.43	CO ₂ -8.5
			N ₂ -56.6	N ₂ -51.92 For m = 0.4591	N ₂ -59.1

Table 2

Comparison of modified model with the model of Jarunghammachote and Dutta (2007) and experiments by Jayah et al. (2003).

Biomass	w (kmol of moisture per kmol of biomass)	m (kmol of air per kmol of biomass)	Gas composition (mole % dry basis)		
			Present model	Model of Jarunghammachote and Dutta (2007)	Experimental results of Jayah et al. (2003)
CH _{1.54} O _{0.622} N _{0.017}	16%	0.33	H ₂ -16.16	H ₂ -16.81	H ₂ -17.00
			CO-17.33	CO-17.86	CO-18.40
			CH ₄ -1.06	CH ₄ -1.05	CH ₄ -1.30
			CO ₂ -12.32	CO ₂ -12.10	CO ₂ -10.60
			N ₂ -53.13	N ₂ -52.18 For m = 0.4472	N ₂ -52.70
CH _{1.54} O _{0.622} N _{0.017}	14%	0.39	H ₂ -13.04	H ₂ -16.80	H ₂ -12.50
			CO-17.60	CO-18.52	CO-18.90
			CH ₄ -1.06	CH ₄ -1.06	CH ₄ -1.20
			CO ₂ -13.65	CO ₂ -11.68	CO ₂ -8.50
			N ₂ -57.11	N ₂ -51.94 For m = 0.4415	N ₂ -59.10

The heat balance was then incorporated in the model which enabled prediction of the gasification temperature of the gasifier. The size of the gasifier was assumed to be small and the heat loss across the gasifier was neglected. The kinetic and potential energy changes in the streams were neglected and the steady state, steady flow energy equation was applied. When the temperature in the gasification zone was T_i and the temperature at the inlet to the gasifier was assumed to be 298 K (25 °C), the enthalpy balance for this process was as below.

$$H_{\text{Reactant}} + Q_{\text{in}} = H_{\text{products}} + Q_{\text{out}} \quad (9)$$

$$H_{\text{Reactants}} = h_{f,\text{biomass}}^0 + w \left[h_{f,\text{moisture}}^0 + \int_{298}^{T_i} C_{p,\text{moisture}} \cdot dT_i \right] \quad (10)$$

$$H_{\text{products}} = \sum_{\text{products}} n_i \left[h_{f,i}^0 + \int_{298}^{T_i} C_{p,i} dT_i \right] + n_{\text{tar}} \cdot h_{f,\text{tar}}^0 \quad (11)$$

As the reaction was considered as adiabatic Q_{in} and Q_{out} were zero. The specific heat (C_p) was assumed as a function of temperature as

shown in Eq. (12) below (Jarunghammachote and Dutta, 2007). T was in Kelvin and C_p was in KJ/kmol K.

$$C_p = a + b \cdot T_i + c \cdot T_i^2 + d \cdot T_i^3 \quad (12)$$

$$\int_{298}^{T_i} C_p(T_i) dT_i = \left[a \cdot T_i + b \cdot \frac{T_i^2}{2} + c \cdot \frac{T_i^3}{3} + d \cdot \frac{T_i^4}{4} \right]_{298}^{T_i} \quad (13)$$

where a, b, c, d were the coefficients values of which were given in Table 3 (Jarunghammachote and Dutta, 2007).

Solution of Eqs. (3)–(9) was done with Athena Visual Studio® to evaluate the composition and gasification temperature.

3. Results and discussion

3.1. Validation of the model

The results from this developed model as stated above were first compared with that of equilibrium model of Jarunghammachote and Dutta (2007). They compared the results of their

Table 3

Coefficients for specific heat for the empirical equation.

Gas species	a	b	c	d	Temperature range (K)
H ₂	29.11	-0.1916×10^{-2}	0.4003×10^{-5}	-0.8704×10^{-9}	273–1800
CO	28.16	0.1675×10^{-2}	0.5372×10^{-5}	-2.222×10^{-9}	273–1800
CO ₂	22.26	5.981×10^{-2}	-3.501×10^{-5}	-7.469×10^{-9}	273–1800
H ₂ O(vapor)	32.24	0.1923×10^{-2}	1.055×10^{-5}	-3.595×10^{-9}	273–1800
CH ₄	19.89	5.204×10^{-2}	1.269×10^{-5}	-11.01×10^{-9}	273–1800
N ₂	28.90	-0.1571×10^{-2}	0.8081×10^{-5}	-2.973×10^{-9}	273–1800

model with the experimental data reported by Jayah et al. (2003). In this study the biomass considered was same as that used by Jayah et al. (2003) for their experimental study. The comparative study with the results of Jarunthammachote and Dutta (2007) and Jayah et al. (2003) with the developed model was presented in Table 1.

3.2. Modification of the model

From the comparative study as presented in Table 1, it was observed that the results predicted by the present model generally agreed with the reference models. However comparing with experimental data the predicted CH_4 fraction from the developed model was quite different from the observed data. Developed equilibrium model predicted very low CH_4 .

The apparent deviation of the data by this model from those obtained from experiments could be attributed to the methane reaction, which tends to deviate from the equilibrium. The other important reaction that influenced the gas composition was the water gas shift reaction. However at high temperature (800 °C) the water gas shift reaction was expected to reach equilibrium.

$$A \times K_2 = \frac{n_{\text{CH}_4} \times n_{\text{total}}}{n_{\text{CH}_4} \times n_{\text{H}_2}} \quad (14)$$

Similar modification was also considered by Jarunthammachote and Dutta (2007) to upgrade their equilibrium model to match experimental data. Initially the value of A is considered as 1 and then it was gradually increased by an increment of 0.5.

Table 2 shows the results of the modified model, with the value of A set at 3.5. Results matched well with that of modified model of Jarunthammachote and Dutta (2007) and also with experimental results reported by Jayah et al. (2003), as shown in Table 2.

In the next stage of validation study, the model of Ptasinski et al. (2007) was considered. The model was validated by taking the biomass as straw, treated wood and untreated wood. A few sample comparative studies with Ptasinski et al. (2007) are given in Fig. 1. The error between the present model and the reference literature was also calculated by taking the model predicted results as datum. The percentage error was calculated as follows.

Error percentage

$$= \frac{\text{Experimental value} - \text{Model predicted value}}{\text{Model predicted value}} \times 100 \quad (15)$$

From Fig. 1, it was observed that the predictions of CO_2 and CH_4 by the developed model were higher than the results obtained by Ptasinski et al. (2007). The percentage error obtained for the CH_4 was high. Mole fraction of CH_4 being very small the estimated error for it was high. The concentrations of CO , H_2 and N_2 obtained from the model were lower than the model of Ptasinski et al. (2007). In their model they found that the optimum operating gasification temperature were 659 °C for straw, 655 °C for treated wood and 642 °C for untreated wood, whereas the gasification temperature predicted by the present model from the heat balance were 671 °C, 663 °C, and 650 °C for straw, treated wood and untreated wood respectively.

Further comparative study was performed with the various experimental results obtained from the literature. Initially the model was compared with the experimental results of Jayah et al. (2003) in which they have reported nine sets of experimental results. First three sets of results of their experiments were compared with the model prediction. Fig. 2 represents the sample comparison of the model with the experimental results of Run. 1–3 respectively in their prescribed conditions.

In the experimental results of Jayah et al. (2003) authors tabulated the measured temperature along the axis of the gasification

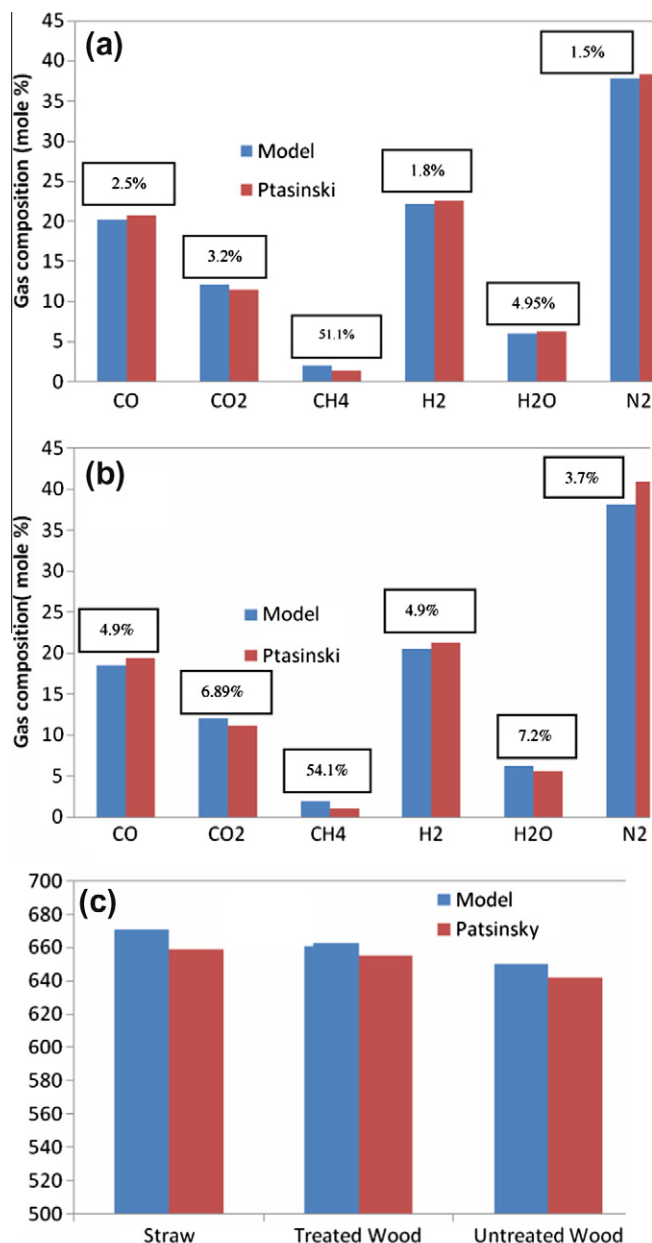


Fig. 1. Comparison of developed model with the model of Ptasinski et al. (2007): (a) for straw with air flow (kg/kg of biomass) = 1.401, (b) for treated wood with air flow (kg/kg of biomass) = 1.628, and (c) gasification temperature for straw, treated and untreated wood.

zone for the air fuel ratio (A/F) of 2.20. Depending upon the location of the thermocouple the temperature of the gasification was in between 800 °C and 1000 °C. In the present model the predicted temperature was 865 °C. Thus it was observed that the model was in very good agreement with the experimental results of Jayah et al. (2003).

Then the present model was compared with the experimental results of Dogru et al. (2002a) in which they used the sewage sludge as biomass. The comparative study has been conducted with the experimental results of Run-3 and Run-5, which is shown in Fig. 3. From Fig. 3 it was observed that the predicted results by the present model for all the mole fractions of gases except CH_4 and N_2 were little higher than the experimental results. It was observed that the temperature of the oxidation zone was varying within the range of 1000 °C to 1100 °C for various A/F ratios (Dogru

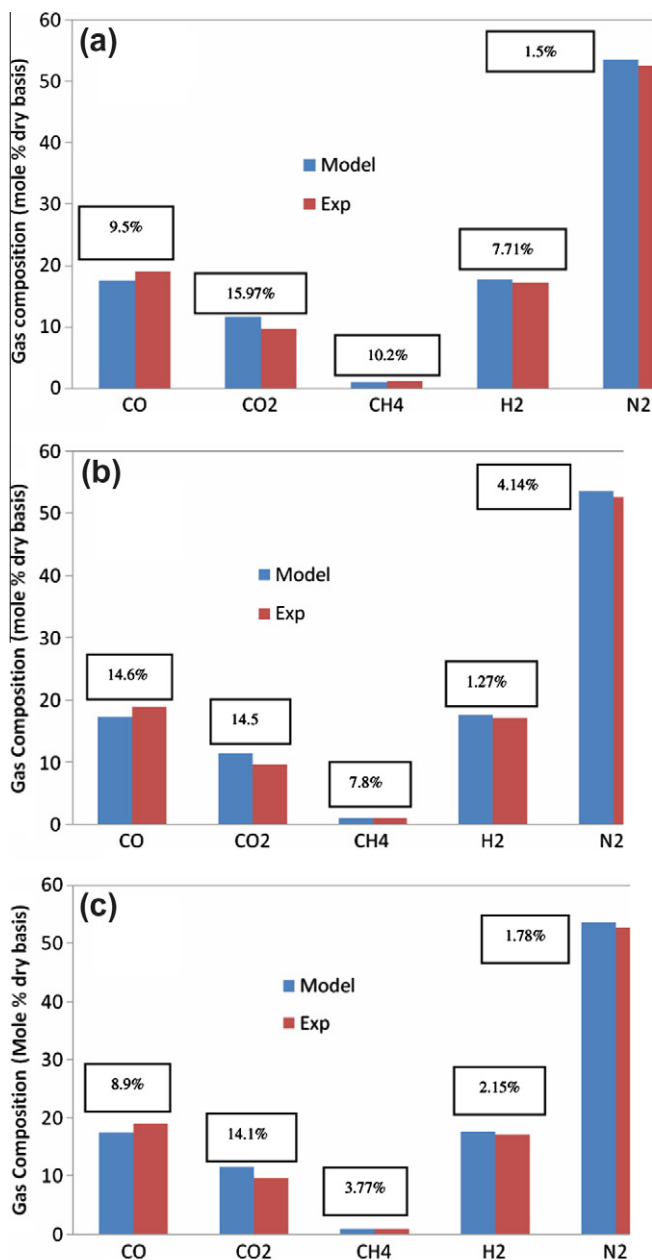


Fig. 2. Comparison of the present model with the experimental results of Jayah et al. (2003): (a) for rubber wood with moisture 18.5%, $A/F = 2.03$, (b) for rubber wood with moisture 16.0%, $A/F = 2.20$, and (c) for rubber wood with moisture 14.7%, $A/F = 2.00$.

et al. 2002a). The gasification temperatures calculated by the present model were 1016 °C and 1034 °C respectively in the respective conditions of Run-3 and Run-5.

The next validation process was done by taking the three experimental results of Pedroso et al. (2005) which were also validated by the theoretical model of Roy et al. (2010). Fig. 4 presented the sample composition of the syngas from the present model, model of Roy et al. (2010) and experimental results of Pedroso et al. (2005).

From the above comparative study of the developed model with some reference model and the experimental study, it could be concluded that assuming tar as a gasification product in the developed model, the results were showing fairly good agreement.

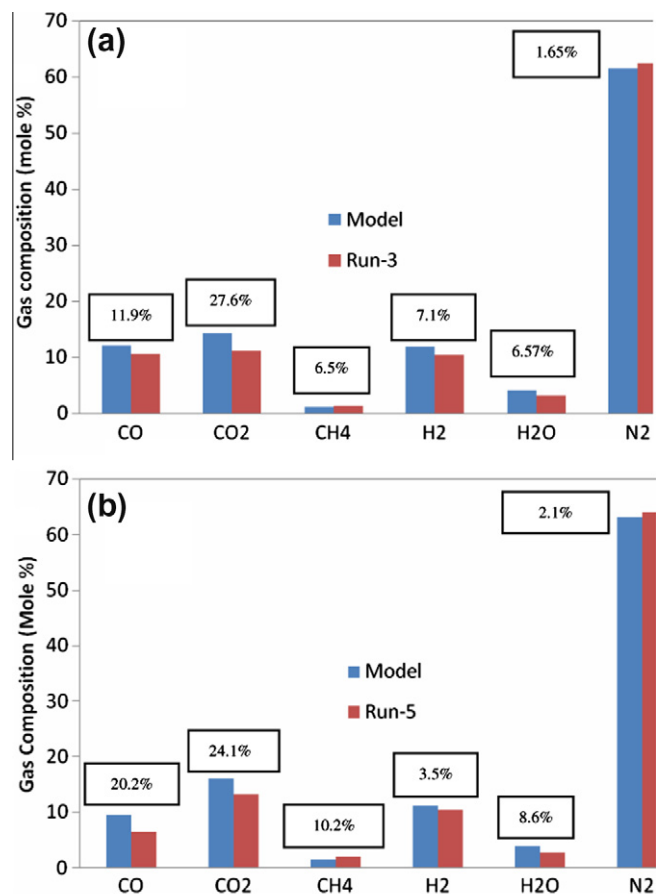


Fig. 3. Comparison of the present model with the experimental results of Dogru et al. (2002a): (a) for sewage sludge with moisture 11.75%, $A/F = 2.28$ and (b) for sewage sludge with moisture 11.75%, $A/F = 2.69$.

3.3. Performance analysis

Results illustrated that the model was showing fairly good agreement with the theoretical as well as experimental results. With acceptable validation of the developed model, a performance analysis of the gasification process by the present model was then done with the variation of air fuel ratio. Then the results were examined with the experimental results of Dogru et al. (2002b). The experimental results were simultaneously plotted with the predictions by the model. Fig. 5 illustrates the performance analysis of the model. In Fig. 5 the performance analyses of a downdraft biomass gasifier based on the developed model is presented. Fig. 5a and b illustrates the variation of gas composition and GCV respectively with the variation of the air fuel ratio. In Fig. 5c the variation of gas production during the gasification process with the variation of mole of moisture per mole of biomass was investigated. The lines within the figures represent the predicted performance of a downdraft gasifier based on the developed model while the discrete points represent the experimental results of Dogru et al. (2002b).

In Fig. 5a along with the performance analysis graph based on the developed model, the experimental results of Dogru et al. (2002b) were plotted against the air fuel ratio (A/F). From Fig. 5a it was observed that due to the increase in A/F ratio mole percentages of N_2 and CO_2 increased whereas the mole % of CO and H_2 decreased. The variation of CH_4 with the variation of A/F ratio was negligible as compared with the other gases. CH_4 concentration decreased from 1.7% to 1.26% when A/F ratio increased from 1.37 to

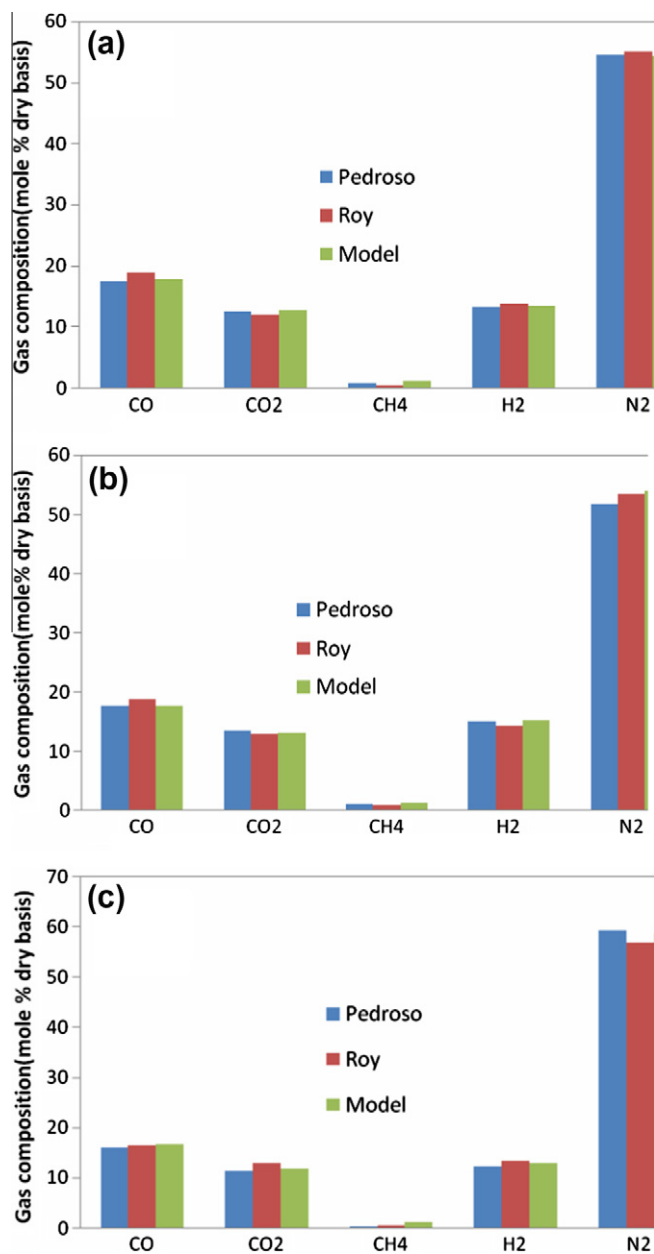


Fig. 4. Comparison of the present model with the experimental results of Pedroso et al. (2005) and the model of Roy et al. (2010): (a) for olive wood with $A/F = 2.03$, (b) for peach wood with $A/F = 2.03$, and (c) for pine wood with $A/F = 2.58$.

1.64. It was noted that due to the increase in air fuel ratio the fuel components (CO, H₂ and CH₄) decreased, as predicted by the present model. This was because the increase in air fuel ratio increased the availability of oxygen to produce more CO₂. The apparent deviation of the experimental results, particularly those for CO and CO₂ concentrations, from the model predictions could be attributed to the specific reactor conditions prevailing during the experiments such as temperature, pressure and also on the design of the gasifier.

From Fig. 5b it was observed that due to the increase in A/F ratio the GCV decreased for the results predicted by the developed model. It was expected that due to the increase in A/F ratio the amount of combustible gases (CO, H₂, and CH₄) decreased and that resulted in decrease in GCV of the producer gases.

Another performance analysis was presented in Fig. 5c in which the variation of gas flow rate was examined with the variation of

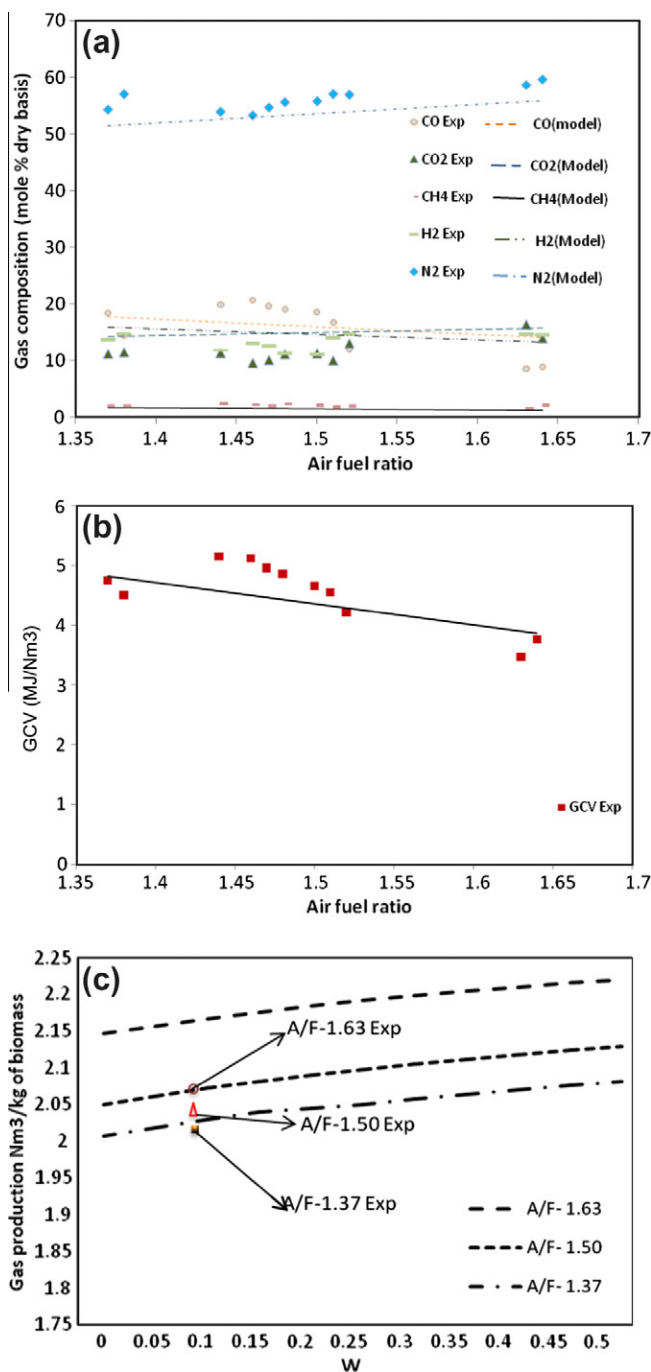


Fig. 5. Performance analysis of the gasifier with developed model and validation: (a) variation of gas composition with air fuel ratio, (b) variation of gross calorific value with air fuel ratio, and (c) variation of gas production with mole of moisture per mole of biomass (w).

moisture content. The air fuel ratio was considered as 1.63, 1.50 and 1.37. Fig. 5c indicated that gas flow rate increased with the increase in moisture content. The possible reason was that when moisture content was increased it would take part in the gasification reaction and increased the gas production except N₂. Experimental results of gas flow rate in Nm³/kg of biomass were also presented by Dogru et al. (2002b) at a specific moisture content of 12.45%. The experimental results were incorporated within the graph and a study was performed in which it was observed that when the air fuel ratio decreased the deviation between the results obtained from the developed model and the experimental results also decreased.

4. Conclusions

This study represents a model for a downdraft fixed bed biomass gasifier. Representative tar composition was used as input parameter in the model. The results obtained by the model showed fairly good agreement with results from the reference model as well as with the experimental investigations. This study has successfully shown that, if the tar mass is accounted for in the mass balance, the rest of the gasification product (permanent gas species, including moisture vapor) may be predicted with considerable degree of accuracy by simple equilibrium model, considered with deviation from the equilibrium for the methane reaction.

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